# CORRELATION OF COMPRESSIVE STRENGTH WITH ULTRASONIC PULSE VELOCITY FOR HIGH PERFORMANCE CONCRETE

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## ABSTRACT

*Nondestructive testing of concrete structures is becoming increasingly popular due to improvement in technology and ease of use. However, evaluation of concrete strength through nondestructive means is one of the most demanding and challenging methods. Ultrasonic Pulse Velocity (UPV) method, one of the most commonly used methods, does not provide strength value of concrete directly. Even though many researchers have developed a variety of correlation models, no particular model is suitable for all types of concrete. This paper presents the correlation models developed for high performance concrete, common in precast concrete industry. High performance was achieved through matrix modification and reduced water content. The water-to-binder ratios selected were 0.35, 0.30, and 0.25. For each series of water-to-binder ratios, four levels of cement replacement with metakaolin were selected: 0, 5, 10, and 15%. Using statistical analysis, empirical models were developed to quantify the effects of water and metakaolin content on concrete compressive strength and ultrasonic pulse velocity. Each of these empirical models is expressed as a function of two independent variables: percent replacement of cement with metakaolin, and water-to-binder ratio. The experimental results and statistical analysis performed indicated that contribution of metakaolin to achieve high-performance is more significant than reduced water content.*

**Keywords:** Compressive Strength, Dynamic Modulus of Elasticity, High-Performance Concrete, Matrix Modification, Metakaolin, Nondestructive Evaluation, Pozzolan, Regression Analysis, Ultrasonic Pulse Velocity.

## INTRODUCTION

Compressive strength is the most common property used to determine the overall quality of the concrete, but other factors that may not be clearly defined also have an impact.
During previous decades the value of compressive strength for concrete to be classified as high strength were much lower.[1] This is a moving target, and with advancement concretes are becoming much stronger and durable. The requirements in Europe for high performance concrete are similar.[2]

To obtain high-performance, several refinements are made to the selection of mix ingredients and their proportions. The first approach is to reduce the water-to-binder ratio. Most high performance concretes have a very low water-to-binder ratio and the workability is often an issue. Concrete that cannot be placed will not meet the specifications of a high performance concrete.[3] Almost all high performance concrete mixtures require some type of high-range water-reducing admixture. Water-reducers allow for less water to be added and at the same time helps achieve proper workability. Pozzolanic materials such as silica fume, fly ash, and metakaolin are now commonly being added to concrete mixtures to improve performance.[4 – 9]

### USE OF METAKAOLIN TO ACHIEVE HIGH PERFORMANCE

The Portland Cement Association (PCA) recommends the use of metakaolin as an additive to cement rather than as a replacement, but research is beginning to show the positive effects it may also have as a replacement.[7] Metakaolin ($2SiO_2$, $Al_2O_3$) is a silica-based pozzolan produced by the calcination of kaolinite after applying extreme heat of 600˚ C - 800˚ C (1112˚ - 1472˚ F). The average particle size of metakaolin is approximately 1 micron ($0.04 \times 10^{-6}$ in.) and it has a specific surface area of about 10,000 $m^2/kg$ (98,300 $ft^2/lb$). For reference, the average cement particle size is about ten times greater than that of a typical metakaolin particle. Metakaolin is an effective pozzolan that is known to increase compressive strength due to its fine particle size. It is also known to increase the tensile and bending strengths.[8] Metakaolin has also been used to improve durability of glass fiber reinforced cement composites in the range of 20 – 25% replacement of cement.[9]

### NONDESTRUCTIVE EVALUATION

Evaluation of concrete properties by nondestructive means is one of the most demanding as well as challenging methods in the civil engineering field. Among many nondestructive test methods Ultrasonic Pulse Velocity is a truly nondestructive method as this method involves only the wave propagation thus causing no damage to the material.[10-11]

In the Ultrasonic Pulse Velocity method, an ultrasonic pulse is generated at a point of the test object and the time of its travel from that point to another point is recorded. If the distance between two points is known then the velocity of the pulse can be computed. The velocity of the wave depends on the elastic properties of the medium through which the wave propagates. Therefore, the propagation of the wave carries the information about the properties of the medium. Thus material properties can be evaluated using an ultrasonic technique in a nondestructive way. The velocity of a compressional wave in a homogeneous, isotropic and elastic medium is given by:

$$V = \left[ \frac{E_d (1-\mu)}{\rho(1+\mu)(1-2\mu)} \right]^{.5} \tag{1}$$

where

$V$ = Compression Wave Velocity
$E_d$ = Dynamic Modulus of Elasticity of Concrete
$\mu$ = Poisson's Ratio
$\rho$ = Density of the material

The method to assess the concrete quality by ultrasonic pulse velocity has been standardized by ASTM C 597. In this method the time of the longitudinal wave to traverse through concrete from a transmitting transducer to receiving transducer is measured. Then the pulse velocity can be computed by the following equation:

$$v = L/T \tag{2}$$

where, $v$ = pulse velocity of longitudinal wave, $L$ = path length, $T$ = transit time

As can be seen from the above equations, the ultrasonic pulse velocity is related to the dynamic modulus of elasticity and density of concrete, hence a correlation can be established between the strength and ultrasonic pulse velocity. However, different factors affect the ultrasonic pulse velocity and the strength of concrete in different ways.[12-13] Thus the strength estimate of concrete with a specific mix proportion by the pulse velocity will not be reliable if a pre-established curve is not available.[14] Researchers in the past came up with different models predicting the concrete strength from the ultrasonic pulse velocity.[15-18]

## RESEARCH SIGNIFICANCE

Ultrasonic Pulse Velocity method does not provide strength value of concrete directly. Hence, correlation of ultrasonic pulse velocity with strength of concrete is desired. Furthermore, as different factors affect this relationship between ultrasonic pulse velocity and compressive strength of concrete, no unique model is suitable for correlating these two parameters for all types of concrete. The intent of this research is to expand on the previous knowledge of cement replacement with metakaolin and combine it with the benefits of low water-to-binder ratios to achieve high performance in concrete. Using statistical regression analysis, empirical models were developed for both compressive strength and ultrasonic pulse velocity as a function of water and silica fume content, as well as correlate ultrasonic pulse velocity with compressive strength.

## EXPERIMENTAL PROGRAM

### TEST SERIES

The materials used in this investigation consisted of: water, cement, coarse aggregate, fine aggregate, metakaolin, and superplasticizer. Coarse aggregate (crushed granite) selected had a maximum nominal size of 9.53 mm (0.375 in.) with a specific gravity of 2.7. The specific gravity of fine aggregate (river sand) was 2.68 and the fineness modulus of 2.95. Metakaolin used for partial replacement of cement met the requirements of ASTM C 618.

Table 1 presents the details of mix ingredients and their proportion. The water-to-binder ratios selected were 0.35, 0.30, and 0.25. For each series of water-to-binder ratio, four levels of cement replacement with metakaolin were selected: 0, 5, 10, and 15%. The amount of superplasticizer was increased as the metakaolin content increased and water-to-binder ratio reduced, to obtain comparable workability.

Table 1 – Test Series and Mixture Proportions

| Mix | Water-to-Binder Ratio | Metakaolin, % | Coarse Aggregate-to-Binder Ratio | Fine Aggregate-to-Binder Ratio |
|---|---|---|---|---|
| 1 | 0.35 | 0 | 1.8 | 1.4 |
| 2 | 0.35 | 5 | 1.9 | 1.5 |
| 3 | 0.35 | 10 | 2.0 | 1.6 |
| 4 | 0.35 | 15 | 2.1 | 1.7 |
| 5 | 0.30 | 0 | 1.8 | 1.4 |
| 6 | 0.30 | 5 | 1.9 | 1.5 |
| 7 | 0.30 | 10 | 2.0 | 1.6 |
| 8 | 0.30 | 15 | 2.1 | 1.7 |
| 9 | 0.25 | 0 | 1.8 | 1.4 |
| 10 | 0.25 | 5 | 1.9 | 1.5 |
| 11 | 0.25 | 10 | 2.0 | 1.6 |
| 12 | 0.25 | 15 | 2.1 | 1.7 |

From each concrete mixture, 6 cylinders of 101.6 mm (4 in.) diameter and 203.2 mm (8 in.) height were cast. All the specimens were covered with plastic lids for 24 hours. They were then demolded and immersed in water until the age of testing (28 days).

### EXPERIMENTAL PROCEDURE

The ultrasonic pulse velocity testing was performed according to the specifications of ASTM C 597. The test was conducted by first measuring the dimensions and weight of the specimen. The density of the cylinder was found by dividing the weight by the total volume. The test started by entering the total length, and a pulse was conducted through the specimen.

The wave was sent from one transducer and received on the other side of the specimen by the receiving transducer. The output from the testing equipment was the velocity of the wave calculated by dividing the length by the time of transmission. The ultrasonic pulse velocity test set-up is shown in Figure 1. Compressive strength tests were performed according to the specifications of ASTM C 39 using a hydraulic testing machine with a digital display.


Fig. 1 Experimental Set-up for Ultrasonic Pulse Velocity Testing.

## EXPERIMENTAL RESULTS AND DATA ANALYSIS

### COMPRESSIVE STRENGTH

Figure 2 shows the average compressive strength for different cement replacement levels with metakaolin. It can be observed that the compressive strength increased for each series with specific water-to-binder ratio with the increase in metakaolin content. This increase appears to be very consistent with increase in metakaolin content, and the increase in strength with each increase (5%) in metakaolin content is in the range of 8 to 10 MPa (1160 to 1450 psi).

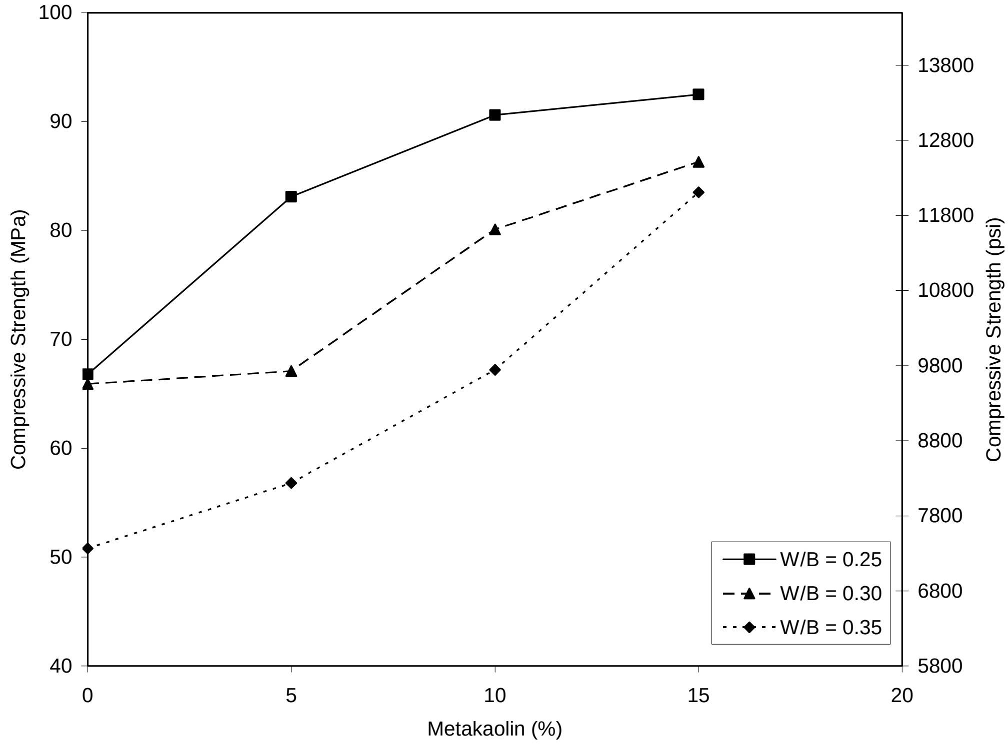


Fig. 2 Effect of Metakaolin Content on Compressive Strength of Concrete.

Figure 3 shows the average compressive strength at different water-to-binder ratios. Compressive strength increases for each series with specific metakaolin content with the reduction in water-to-binder ratio. The trend is similar to Figure 2 in the sense that the compressive strength increases consistently with the reduction from one water-to-binder ratio to the next. The typical increase in strength with each reduction (0.05) in water-to-binder ratio is approximately 10 MPa (1450 psi). Concrete with 15% metakaolin yielded higher compressive strengths than other mixes, for any given water-to-binder ratio. Control mixes with no metakaolin yielded the lowest compressive strengths for each water-to-binder ratio studied in this investigation.

The highest strengths were expected at the lowest water-to-binder ratio and this was found to be true. The highest compressive strength obtained was 92.5 MPa (13400 psi) from a water-to-binder ratio of 0.25 and a cement replacement with metakaolin by 15%, an 82% increase when compared with control mixture with a water-to-binder ratio of 0.35. In essence, compressive strength was observed to be directly proportional to metakaolin content and inversely proportional to water-to-binder ratio. Thus, one can achieve high compressive strength with increased metakaolin content and reduced water-to-binder ratio, provided measures are taken to maintain good workability.

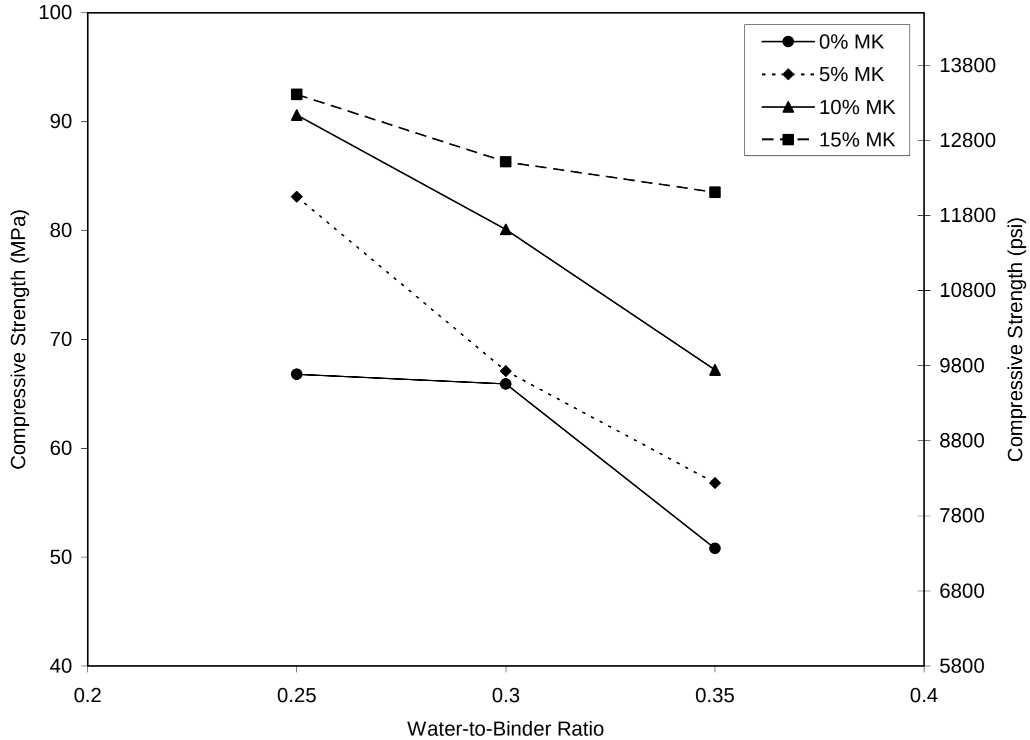


Fig. 3 Effect of Water-to-Binder Ratio on Compressive Strength of Concrete.

## ULTRASONIC PULSE VELOCITY

Graphical representations of the effect of metakaolin and water-to-binder ratio on ultrasonic pulse velocity in concrete are presented in Figures 4 and 5, respectively. The pulse velocity and dynamic modulus of elasticity were obtained with Poisson's ratio of 0.20. Figure 4 shows that as the metakaolin content was increased the ultrasonic pulse velocity also increased moderately. Concrete with no metakaolin yielded the lowest values of pulse velocity, and 15% metakaolin, in general yielded the highest velocities (5 to 15% increase). This was observed to be true at all water-to-binder ratios. In mixes where 0% and 5% metakaolin was present, pulse velocities seemed not to change significantly. In mixes where 10% and 15% metakaolin was used, pulse velocities were similar to each other, but much higher than those obtained at 0% and 5%.

A similar trend could be observed with the reduction in water-to-binder ratio. As the water-to-binder ratio was decreased an increase in the pulse velocity was observed. Mixes with a water-to-binder ratio of 0.25 yielded the highest pulse velocities, while the lowest values were observed with 0.35. These results confirm the general predictions that pulse velocity is an indirect method of testing the quality of a concrete, and higher values of water-to-binder ratio lead to lower quality concrete.

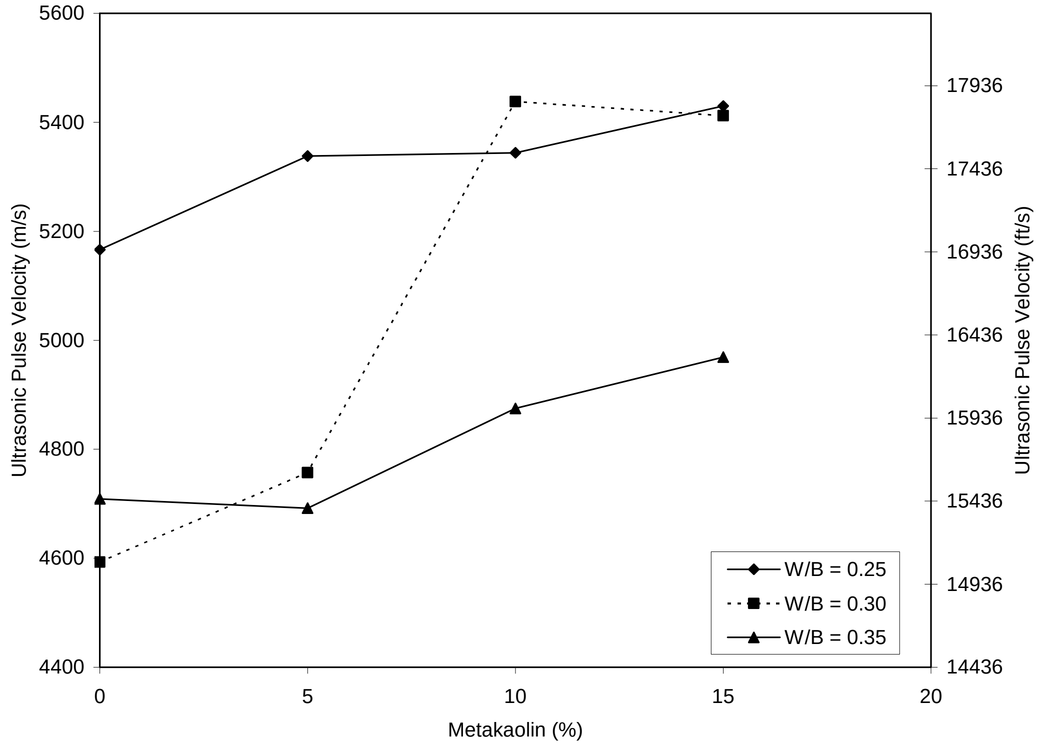


Fig. 4 Effect of Metakaolin Content on Ultrasonic Pulse Velocity in Concrete.

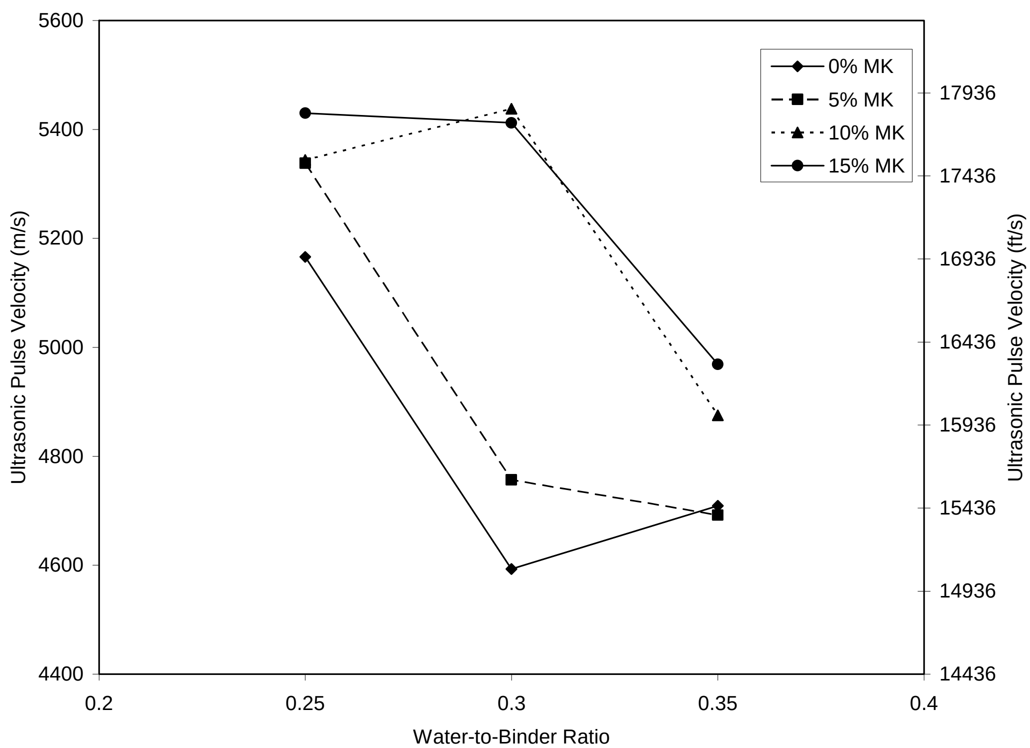


Fig. 5 Effect of Water-to-Binder Ratio on Ultrasonic Pulse Velocity in Concrete.

The dynamic modulus of elasticity was obtained directly from the pulse velocity. The highest values of pulse velocity and dynamic modulus of elasticity were obtained for mixes with 15% cement replacement with metakaolin and water-to-binder ratios of 0.25. In essence, ultrasonic pulse velocity and dynamic modulus of elasticity were observed to be directly proportional to metakaolin content and inversely proportional to water-to-binder ratio.

## STATISTICAL CORRELATION OF COMPRESSIVE STRENGTH TEST DATA

In this statistical analysis, water-to-binder ratio and metakaolin content were the factors used in a two factor factorial design to analyze the response (compressive strength). Regression analysis was performed on the compressive strength test results to obtain the best-fit curve. The root mean square residual (RMSR) was minimized through optimization process to obtain a model that best fit the data. The quadratic model that best fits the analyzed data is expressed by the following quadratic equation:

$$Y = a + bX_1 + cX_2 + dX_1X_2 + eX_1{}^2 + fX_2{}^2$$

Where:

$Y$ = Model equation for Compressive Strength
$X_1$ = Water-to-Binder Ratio
$X_2$ = Metakaolin Content (% by weight of cement)
$a, b, c, d, e,$ and $f$ = Regression coefficients

Through solving the model equations by optimizing the least amount of error to obtain regression coefficients and substituting them in the quadratic equation for compressive strength, the model equation becomes:

$$Y = 104.26 - 65.93X_1 + 0.37X_2 + 4.65X_1X_2 - 259.09X_1{}^2 + 0.0009436X_2{}^2 \qquad (3)$$

To account for the error in this model, the root mean square residual (RMSR) was calculated, and for the pulse velocity model equation it was found to be 4.64. The ideal value for RMSR is zero. The RMSR of 4.64 and is considered to be very accurate due to its proximity to zero.

## STATISTICAL CORRELATION OF PULSE VELOCITY TEST DATA

A similar procedure of regression analysis was performed on ultrasonic pulse velocity data in concrete. Minimizing the error through optimization process, regression coefficients for the quadratic equation was obtained. The quadratic model that best represents the data is:

$$Y = a + bX_1 + cX_2 + dX_1X_2 + eX_1{}^2 + fX_2{}^2$$

Where:

$Y$ = Model equation for Pulse Velocity
$X_1$ = Water-to-Binder Ratio
$X_2$ = Metakaolin Content (% by weight of cement)

*a, b, c, d, e,* and *f* = Regression coefficients

Through solving the model equations by optimizing the least amount of error to obtain regression coefficients and substituting them in the quadratic equation for ultrasonic pulse velocity, the model equation becomes:

$$Y = 8923.43 - 22225.57X_1 + 15.75X_2 + 89.95X_1X_2 + 28097.46{X_1}^2 - 0.92{X_2}^2 \qquad (4)$$

To account for the error in this model, the root mean square residual (RMSR) was calculated, and for the pulse velocity model equation it was found to be 127.33. The ideal value for RMSR is zero. However, the variability associated with concrete makes it difficult to achieve RMSR of zero, especially for ultrasonic pulse velocity. It is generally accepted that the presence of aggregates in concrete is the main source of variability for ultrasonic pulse velocity. However, its effect is not that pronounced with compressive strength. The model RMSR calculated clearly confirms this.

## CORRELATION OF PULSE VELOCITY AND COMPRESSIVE STRENGTH

One of the objectives of this experimental investigation was to correlate the ultrasonic pulse velocity in concrete to the compressive strength. Pulse velocity is thought to be a relative indicator of the quality of a concrete mix. However, there is no direct relation between compressive strength and pulse velocity. Hence, correlation of pulse velocity to compressive strength must be made through experimental procedures before one could quantitatively use pulse velocity to measure concrete performance. Correlation between strength and pulse velocity was performed through statistical analysis and optimization.

A graphical representation of the correlation of pulse velocity and compressive strength for different levels of metakaolin content is shown in Figure 6. Graph showing the relation between pulse velocity and compressive strength for different water-to-binder ratios is presented in Figure 7. The equations used to generate those curves and their corresponding root mean square residuals are presented in Tables 2 and 3. It should be noted that for correlation between pulse velocity and compressive strength, a linear function was the most accurate model equation obtained. For reference, Y corresponds to compressive strength and the X corresponds to ultrasonic pulse velocity.

It is clear from the compressive strength and ultrasonic pulse velocity results and the models developed, the relationship between strength and pulse velocity for plain concrete and concrete modified with metakaolin are different. Thus, the correlations established are specific to the mix proportions and matrix modifications studied in this investigation.

Table 2 Equations relating Pulse Velocity and Compressive Strength for various Metakaolin Contents

| MK % | Model Equation | RMSR |
|---|---|---|
| 0 | Y = 0.0065X + 30.76 | 4.72 |
| 5 | Y = 0.017X - 12.70 | 4.95 |
| 10 | Y = 0.020X - 24.12 | 4.19 |
| 15 | Y = 0.008X + 43.33 | 3.93 |

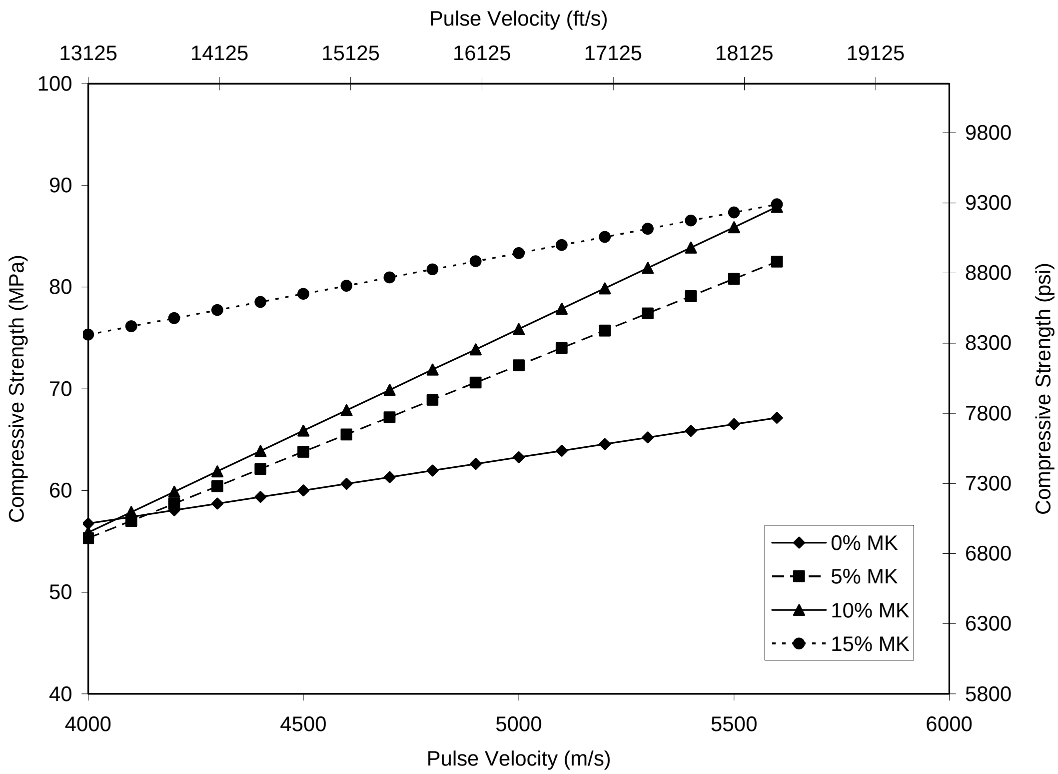


Fig. 6 Graphical Representation of Pulse Velocity and Compressive Strength Model for various Metakaolin Contents.

Table 3 Equations relating Pulse Velocity and Compressive Strength for various Water-to-Binder Ratios

| W/B | Model Equation | RMSR |
|---|---|---|
| 0.35 | Y = 0.025X - 53.74 | 4.68 |
| 0.3 | Y = 0.017X - 10.83 | 4.83 |
| 0.25 | Y = 0.023X - 39.36 | 6.76 |

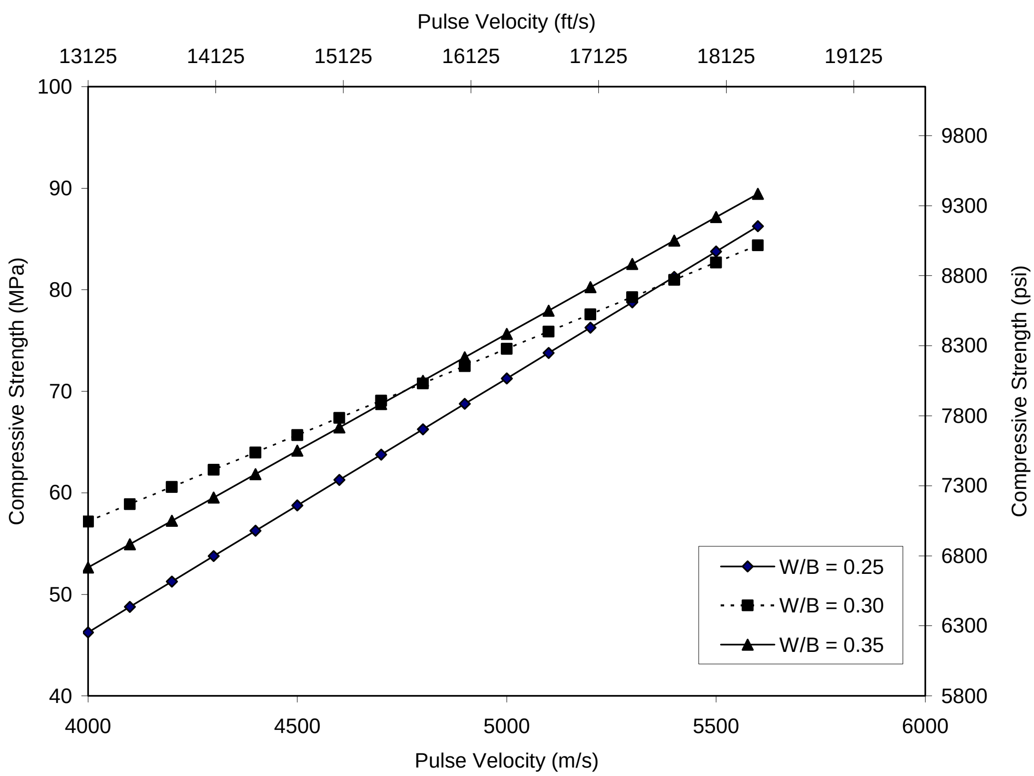


Fig. 7 Graphical Representation of Pulse Velocity and Compressive Strength Model for various Water-to-Binder Ratios.

## SUMMARY AND CONCLUSIONS

Based on the experimental data collected and statistical analysis performed in this investigation, the following conclusions were drawn:

- The compressive strength showed an increase with increased levels of metakaolin content at all water-to-binder ratios. The lowest strength was found in plain concrete with 0.35 water-to-binder ratio, and the highest strength was with a water-to-binder ratio of 0.25 and metakaolin level of 15%.

- Ultrasonic pulse velocity increases with increased amounts of metakaolin. The lowest values of pulse velocity were obtained in plain concrete (control) samples with 0.35 water-to-binder ratio. The highest values were obtained with 0.25 water-to-binder ratio and 15% cement replacement with metakaolin. This supports the idea that pulse velocity could be related to the compressive strength due to similar trends observed with compressive strength.
- A clear trend could be seen with the ultrasonic pulse velocity results, when the effect of both the water-to-binder ratio and the metakaolin content were included and regression analysis was performed. A quadratic model was developed to best fit the data by optimizing the amount of error.
- A quadratic equation was also found to be the best fit for the compressive strength when regression analysis was performed to quantify the effects of metakaolin content and water-to-binder ratio.
- The relation between pulse velocity and compressive strength was best modeled through a linear equation with the pulse velocity being the independent variable.

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